Obstacles Associated with Winding Resistance Measurements of Power Transformers

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Abstract

DC Winding Resistance is a simple concept that relies on the fundamental application of Ohm's Law. DC Winding Resistance is a powerful tool for determining continuity in power transformer winding circuits; specifically, connections and tap changer contacts. However, performing DC Winding Resistance tests often presents several technical difficulties that must be overcome. The magnetizing inductance of power transformers must be removed through saturation of the core steel. To accomplish saturation, DC voltage or DC current must be applied or injected, respectively. The magnitude of DC signals will directly affect the time to saturation. Various techniques can be applied, such as winding assist, to speed-up and increase the effectiveness of the saturation process. This paper will present the obstacles associated with performing DC Winding Resistance tests, saturation techniques, safety considerations, demagnetization, and case studies.

Introduction

The DC Winding Resistance test is used routinely in the field to validate and assess the continuity of the current carrying path between terminals of a power transformer winding. The DC Winding Resistance test is looking for a change in the continuity or real losses of this circuit, generally indicated by high or unstable resistance measurements. The diagnostic reach of the DC Winding resistance test is to identify problems such as loose lead connections, broken winding strands, or poor contact integrity in tap changers. In addition to the winding, there are several more components that are part of the transformer's current carrying path:

- Bushings and Bushing Connections

    - Draw Leads
    - Draw Lead Pins
    - Pad Connections

- Tap Changers (LTC and DETC)

    - Barrier Board Connections
    - Selector Switches
    - Diverter Switches
    - Reversing Switches

- Windings

    - Strands
    - Cross-Overs
    - Tap Leads

Measurements

The goal is to isolate and measure only the winding resistance for a specific phase and winding. However, depending on the winding configuration, Delta (open or closed), Wye, Auto, and Zig-Zag, and the fact that winding resistance measurement can only be performed between terminals, the measured result may be a combination of windings and not a specific winding. All Delta winding configuration measurements often cause confusion because a single winding cannot be isolated by any terminal pair. Also, in specific applications, such as tertiary or stabilizing windings, the open or closed status of the Delta winding creates additional confusion.

The Winding Resistance measurement circuit includes 3 components - a DC source (V or I), a Voltmeter, and a Current meter, and by simultaneously measuring voltage and current determines resistance by Ohm's Law.

As simple as the DC Winging measurement appears, several factors should be considered.

Measurement Ranges

Understanding the expected resistance values is important for setting up and performing a DC Winding Resistance measurement. The most modern winding resistances instruments have the ability to measure very low resistances values in the micro-Ohm ($\mu\Omega$) range up to notably higher resistance values in the kilo-Ohm (kΩ) range. However, typical transformer winding resistances generally range from a few milli-Ohms (mΩ) to several Ohms (Ω).

It is recommended to review previous results or consult the factory test report for determining the expected results. This will allow the optimum ranges on the test instrument to be selected. It is always best to run all meters close to full range, above 70%, if possible. In the case of auto-ranging instrumentation, always verify that an overload condition has not occurred; this could greatly affect accuracy in the reading.

Static and Dynamic Measurement Types

There are two distinctive types of DC Winding Resistance measurements that can be applied, Static (Standard) and Dynamic (Advanced).

Static – This is the standard test that is performed to measure the actual resistance value of a transformer winding and associated series components. The static measurement produces a single, temperature dependent value in Ohms (Ω).

Dynamic – This measurement is typically applied to load-tap changing (LTC) transformers. The dynamic winding resistance measurement tracks the changing resistive behavior as the LTC operates. Knowing that a LTC follows the make before break concept, any unusual changes, such as, loss of continuity, may indicate premature wear or fault with the LTC, specifically the diverter contacts.

Kelvin Connections

The Kelvin 4-wire method is the most effective method used to measure very low resistance values. The Kelvin 4-wire method will exclude the resistance from the measurement circuit leads and any contact resistance at the connection points of these leads. The concept of the Kelvin 4-wire method is to apply the voltage and current leads separately. This is shown in Figure 1.
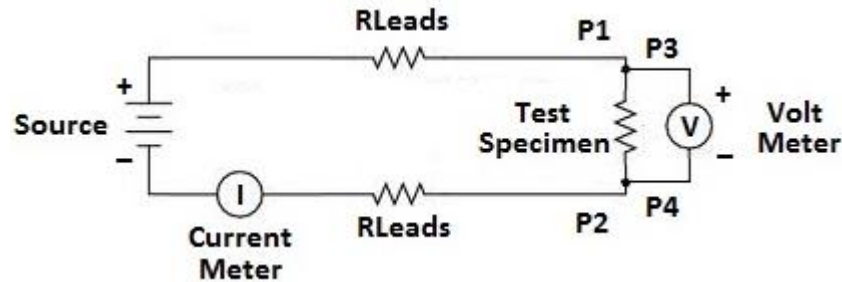
Figure 1 - The Kelvin 4-wire method

Connection points P1 and P2 are associated with the current injection and current measurement, and points P3 and P4 isolate the voltage measurement across the test specimen. Another subtle application of the Kelvin 4-wire method that should be noted, is placing the voltage sense leads (P3 and P4) "inside" the current leads (P1 and P2). This helps ensure that any undesired voltage drops remain outside the intended resistance measurement.

Saturation

The implication of the transformer core's state of saturation makes the "simple in concept" test much more troublesome to users. Understanding the influence of the transformer core on the DC Winding Resistance measurement and why core saturation is a prerequisite for this test is challenging. To obtain the desired DC Winding Resistance measurement, the resistive component of the winding must be isolated; this requires saturation of the transformer's magnetic circuit. Saturation occurs when all of the magnetic domains are successfully aligned in the same direction.

By using Faraday's Law: $$V = -N\frac{\Delta\Phi}{\Delta t} \quad,$$

it can be stated that the saturation process is dependent on the voltage applied across the terminals of a transformer. Intuition often leads us to believe it is current. However, higher currents produce greater voltage drops. From an application standpoint, it is important to understand the volt-amperes (VA) relationship, so that V can be maximized.

The transformer winding appears to be a simple RL circuit. However, L, or the inductive component is made up of the leakage reactance of the winding, and the magnetizing reactance of the core. It is these inductive components that must be minimized through saturation. Figure 2 illustrates the RL basic components.
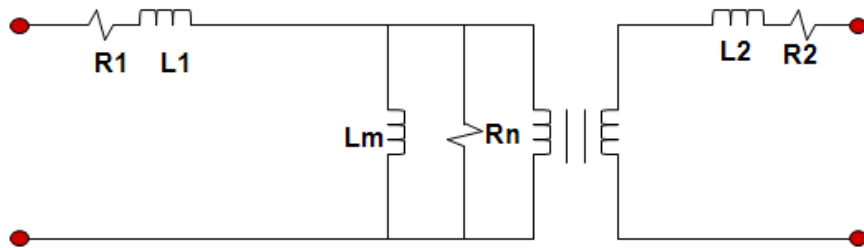
Figure 2 - Basic Transformer Impedance Model

These inductances work in conjunction with the DC Winding Resistance and create a "not so simple" time constant. This time constant could be seconds or it could be minutes. Figure 3 shows a typical voltage and current response for a transformer winding, where 12 VDC has been applied.
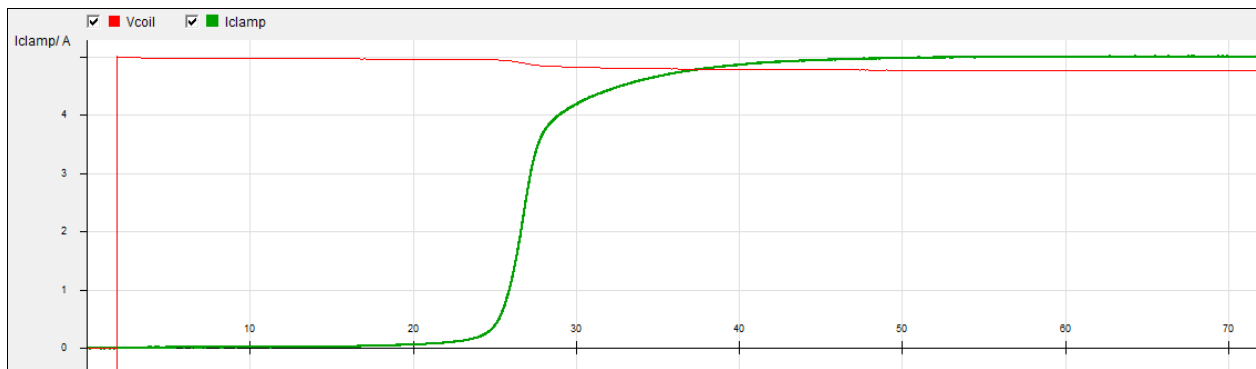
**Figure 3** - Saturation Response: Voltage and Current Signals

There are techniques and good practices that will improve the saturation process. If normal current injection methods are not sufficient and effective, there are additional advanced techniques to aid in saturation. Time to saturation can be shortened by either applying more current, re-directing current flow in Yn or yn windings, or using a combination of HV and LV windings.

Recommended Techniques:

1. Apply the highest possible terminal voltage without exceeding the recommended winding rating limits. To increase saturation performance, it is important to maximize the terminal voltage. However, there are some limitations. The current through a winding should not exceed 15% of the rated current. Limiting the current minimizes the chance of overheating, which could cause a change in resistance or thermal instability.

2. Maintain the direction of the magnetic domains between tests. Be aware of the terminal polarity. This may not be optimal when testing a Delta winding.

3. Re-directing current flow in a Wye winding with an accessible neutral takes advantage of the use of all 3 phases to align magnetic domains. This aligns flux direction in core by tying together 2 terminals.

   - X1-X0: Inject into X1 and return through (X2 and X3) tied together; measure voltage across X1-X0
   - X2-X0: Inject into X2 and return through (X3 and X1) tied together; measure voltage across X2-X0
   - X3-X0: Inject into X3 and return through (X1 and X2) tied together; measure voltage across X3-X0

   Figure 4, shown below, is an example of re-direct current in Wye winding with an accessible neutral: " X1-X0: Inject into X1 and return through (X2 and X3) tied together; measure voltage across X1-X0"
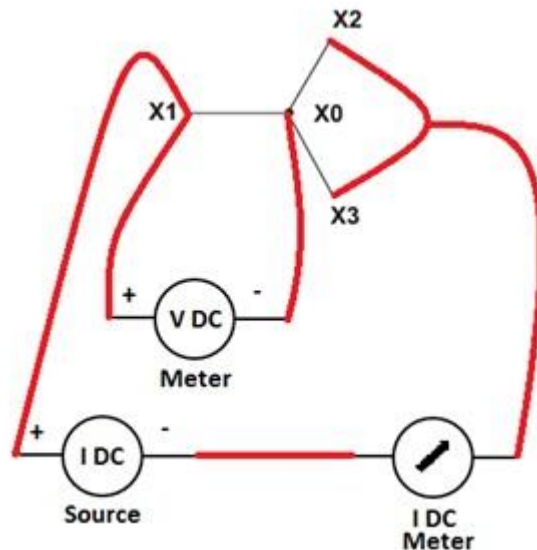
Figure 4 - Redirecting Current through a Wye Winding with Accessible Neutral

4. Use the HV and LV windings at the same time to assist in saturation; must be same phase and direction.

   - X1-X0: Inject into H1 and tie (H3 and X1) together and return through X0; measure voltage across X1-X0
   - X2-X0: Inject into H2 and tie (H1 and X2) together and return through X0; measure voltage across X2-X0
   - X3-X0: Inject into H3 and tie (H2 and X3) together and return through X0; measure voltage across X3-X0

   Figure 5, shown below, is an example of using both HV and LV windings: " X1-X0: Inject into H1 and tie (H3 and X1) together and return through X0; measure voltage across X1-X0"
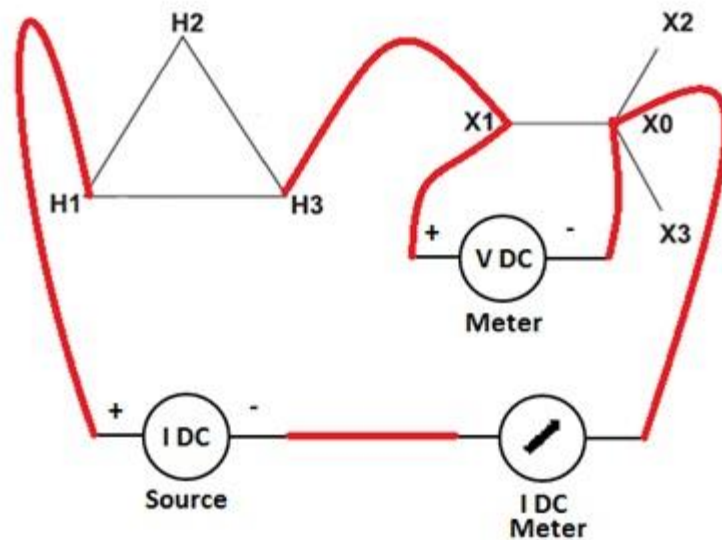
**Figure 5** - Combining both HV and LV Winding

Safety

- Strictly follow all local safety policies and procedures

- Potential high voltage is present when applying the DC output to test objects with a high inductance

- As long as energy is flowing in the measurement circuit", NEVER connect or disconnect test objects and/or cables.

- Always swap leads at bushing terminals and never at test equipment.

- Use separate clamps for current and voltage connections on both sides of the test object to avoid hazards in case one clamp falls off during the test.

Magnetization

The saturation process leaves the transformer core in a magnetized state. For most transformer applications, this is usually considered benign; however, magnetized transformers produce higher inrush currents upon energization. When in doubt, the manufacturer should be consulted.

One side effect of core saturation is that it can influence other diagnostic tests, such as Turns Ratio and specifically, Exciting Currents and Sweep Frequency Response Analysis (SFRA). It is recommended to perform the DC Winding Resistance last to avoid contaminating the above mentioned test results. At the same time, exciting current tests and SFRA tests can be used to confirm and validate the presence or absence of magnetization. Figure 6 illustrates how magnetization can affect exciting currents results. In this example, the expected pattern of two

similar high and one low is slightly distorted. As it is in this case, Phase C is often the worse because that is the phase that DC was last applied to during testing.
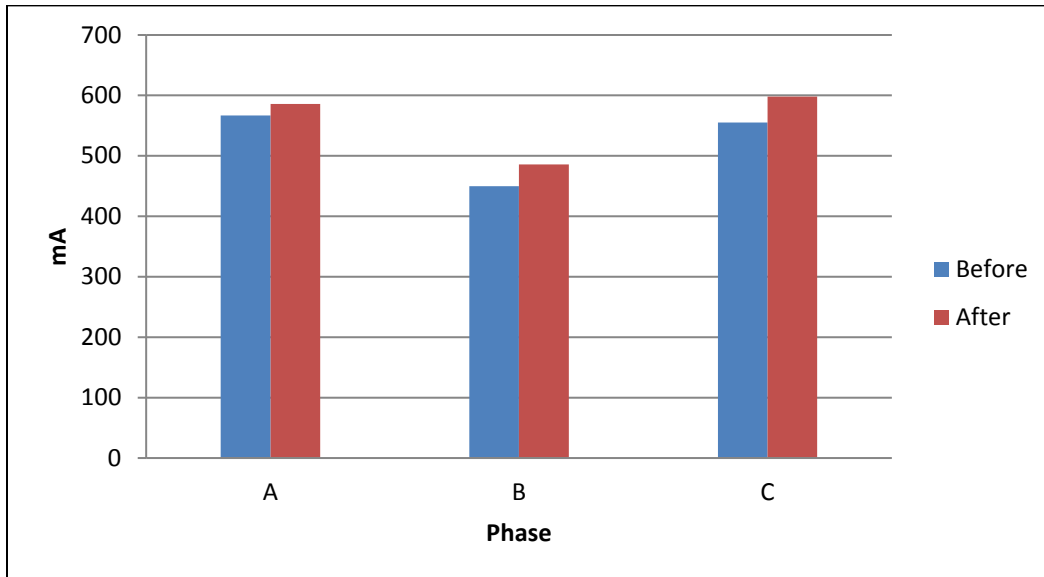
Figure 6 - Exciting Current Patterns (with and without magnetization)

At times, it may be required to demagnetize the transformers. There are two techniques that can be used to demagnetize a transformer.

1. Apply a decreasing AC voltage. This method is not practiced often due to the cost, size and complexity of such equipment for field use. This method would pull the BH curve, see Figure 7, to zero.

2. Apply DC power to the transformer windings and reverse the polarity of the applied source a number of times while reducing the voltage, current, and applied time until the core is demagnetized. Again, the focus is to pull the BH curve to zero.
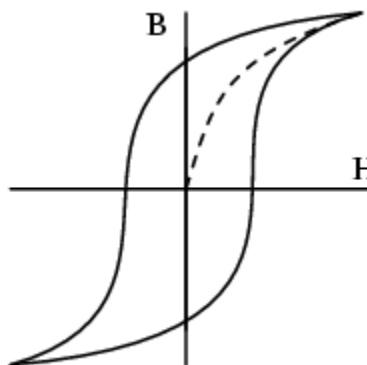
Figure 7 - BH Curve

Analysis of Results

Failure Modes Detected by Winding Resistance

Winding resistance is a diagnostic tool that focuses on Thermal and Mechanical failure modes. The winding resistance test is very useful in identifying:

- Defective DETC or LTC (contacts)
- Poor Connections
- Shorted Circuited Turns
- Open Circuits and Turns

Such problems can generate significant heat during normal operation. It is recommended to review DGA results to provide supporting information that a heating condition exists.

Recommended Limits

Winding resistance test results are interpreted based on comparison. Individual phase measurements (Wye) or terminal measurements (Delta) are compared. Comparisons may also be made with the original factory results or previous test results. When comparing data from different test dates, the results should be normalized to a common reference temperature. It is expected that the measurements should be within 2% of each other [1].

Temperature Correction

The temperature conversion formula is as follows [2]:

$$R_s = R_m \left[\frac{T_s + T_k}{T_m + T_k} \right]$$

where:
|		
Rs	=	resistance at desired temperature Ts
Rm	=	measured resistance
Ts	=	desired reference temperature (°C)
Tm	=	temperature at which resistance was measured (°C)
Tk	=	234.5°C (copper)
Tk	=	225°C (aluminum)

Identifying Saturation Integrity

To obtain valid winding resistance measurements, core saturation must occur. Often, experience is the best option for knowing how to identify saturation. The behavior of the measurement is generally inconsistent depending on the transformer design and configuration. Delta windings and preventative autotransformers in the LTC circuit are a few examples of obstacles that will affect the saturation process. Even after several minutes, saturation may appear complete, just to

then change again. It is important on difficult units to document test parameters including approximate saturation time if the unit has been tested before.

Once the testing is complete, an analysis is often enhanced by plotting the data, which in many cases is more helpful than viewing the data in tabular form. Figure 8, shown below, illustrates winding resistance data on a LTC that is exhibiting incomplete saturation. In both examples, early measurements are higher than expected. By viewing the plotted data, it is clear that core saturation has not occurred, and several measurements at the beginning of the test should be considered invalid.
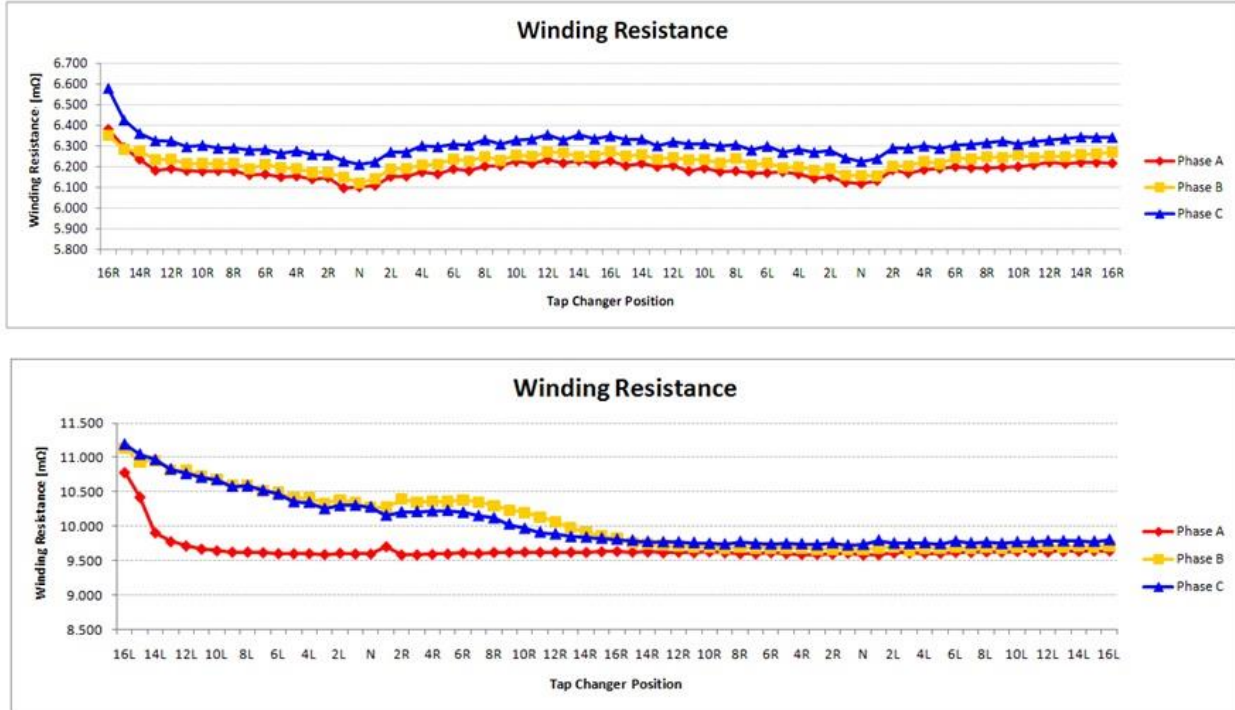

Figure 8 - Incomplete Saturation

Case Studies

Overheated Tap Changer Leads

In this case study, the winding resistance measurements produces significantly higher readings on LTC positions 14R and 4L for Phase B, see Figure 8. Normal measurements were expected to be in the 25-30 mΩ range. The 14R and 4L measurements clearly exceeded the recommended limit of 2%. At first glance, it appears unusual that separate LTC positions produce questionable results. After reviewing the LTC nameplate information, see Table 1 below, it shows that LTC positions 14R and 4L share a common tap lead (#7).
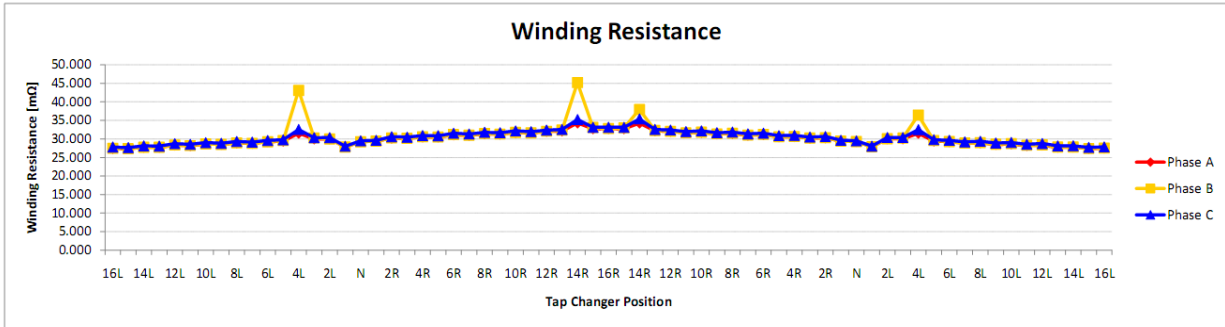
Figure 9 - Winding Resistance Measurements on LTC

| POS	Volts	LTC		
	X1-X2-X3	A	B	9
16R	15180	8	8	
15R	15095	7	8	
14R	15010	7	7	
13R	14920	6	7	
12R	14835	6	6	
11R	14750	5	6	
10R	14660	5	5	
9R	14575	4	5	M
8R	14490	4	4	
7R	14405	3	4	
6R	14320	3	3	
5R	14230	2	3	
4R	14145	2	2	
3R	14060	1	2	
2R	13970	1	1	
1R	13885	0	1	
N	13800	0	0	
1L	13715	8	0	
2L	13360	8	8	
3L	13540	7	8	
4L	13455	7	7	
5L	13370	6	7	
6L	13280	6	6	
7L	13195	5	6	
8L	13110	5	5	
9L	13025	4	5	K
10L	12940	4	4	
11L	12850	3	4	
12L	12765	3	3	
13L	12680	2	3	
14L	12590	2	2	
15L	12505	1	2	
16L	12420	1	1	

Table 1 - LTC Nameplate

Upon further investigation, clear over-heating of connection #7 was observed. This overheating is shown below in Figure 10.

Figure 10 - Overheating of Connection #7

Poor LTC Contact

Winding resistance measurements were performed on a load-tap changing transformer with a resistor-type LTC. All odd positions failed. Phase X3-X0 had higher than expected measurements The resistance measurements were consistently higher. This is shown in Figure 11.
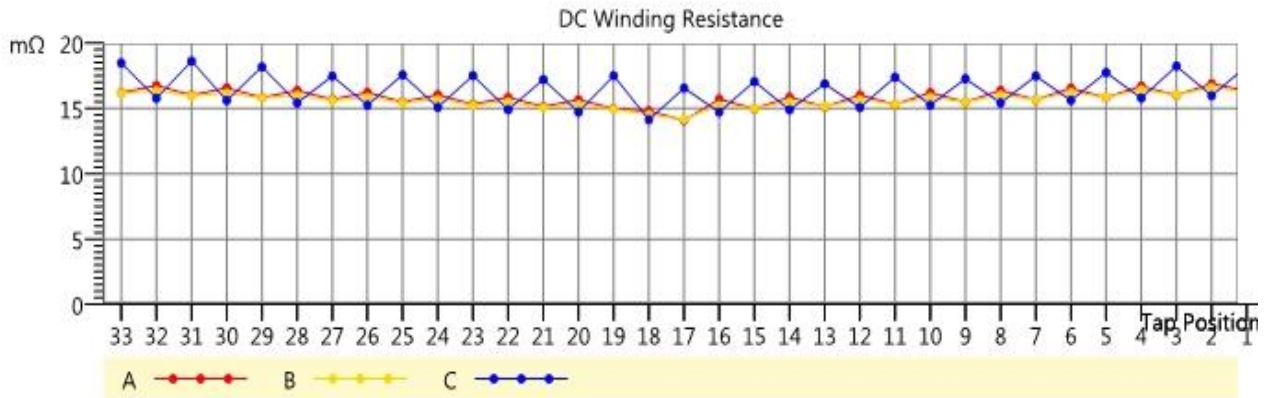
Figure 11 - Winding Resistance Measurement (poor odd positions on Phase C)

When measurements fail consistently in a pattern, as shown above, "in common" components should be investigated. This pattern indicates the problem is mostly associated with the diverter switch main (non-arcing) contacts or associated leads. See Figure 12 below shows one side of the diverter switch.

Figure 12 – Diverter Switch

<u>Conclusion</u>

This paper shares insight associated with performing DC Winding Resistance tests, saturation techniques, safety considerations, and demagnetization, and provides two case studies. The salient points of this paper are summarized as follows:

1. The Winding Resistance measurement circuit includes 3 components - a DC source (V or I), a Voltmeter, and a Current meter, and by simultaneously measuring voltage and current determines resistance by Ohm's Law.

2. The DC Winding Resistance test provides a diagnostic tool that focuses on thermal and mechanical failure modes. The winding resistance test identifies problems such as loose lead connections, broken winding strands, or poor contact integrity in tap changers.

3. DC Winding Resistance results are interpreted based on comparison, and are corrected for temperature.

4. Transformer core saturation is a prerequisite for obtaining valid winding resistance measurements. Understanding the influence of the transformer core on the DC Winding Resistance measurement is challenging. Experience best equips a user in successfully identifying complete saturation of the transformer's magnetic circuit.

References

[1] IEEE Std 62-1995, "Guide for Diagnostic Field Testing of Electrical Apparatus – Part 1: Oil Filled Power Transformers, Regulators, and Reactors".

[2] P. Gill: "Electrical Power Equipment Maintenance and Testing" *Second Edition,* CRC Press, 2009

[3] C. L. Sweetser, "The Importance of Advanced Diagnostic Methods for Higher Availability of Power Transformers and Ancillary Components in the Era of Smart Grid", *IEEE Power Engineering Society Summer Meetings,* Detroit, MI, USA, July 22-26, 2011

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